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Effects of liming and artificial acid rain on Collembola and Protura in coniferous forest

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With 5 figures

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Contents

1. Introduction

In large areas of North America and Europe, the acidity of rain and snow has increased markedly during recent decades (Anon. 1977, LIKENS *et al.* 1979). This is mainly due to long-range transported industrial air pollutants. In Scandinavia, the acidified precipitation is primarily caused by industrial outlets in central Europe (DOVLAND *et al.* 1976, Anon. 1977). One of the objectives of the Norwegian "SNSF project" (OVERREIN *et al.* 1980) was to study effects of artificial acidification, and liming, on the forest soil fauna. This fauna, which is species rich and integral to the processes of decomposition, is susceptible to changes in the soil environment.

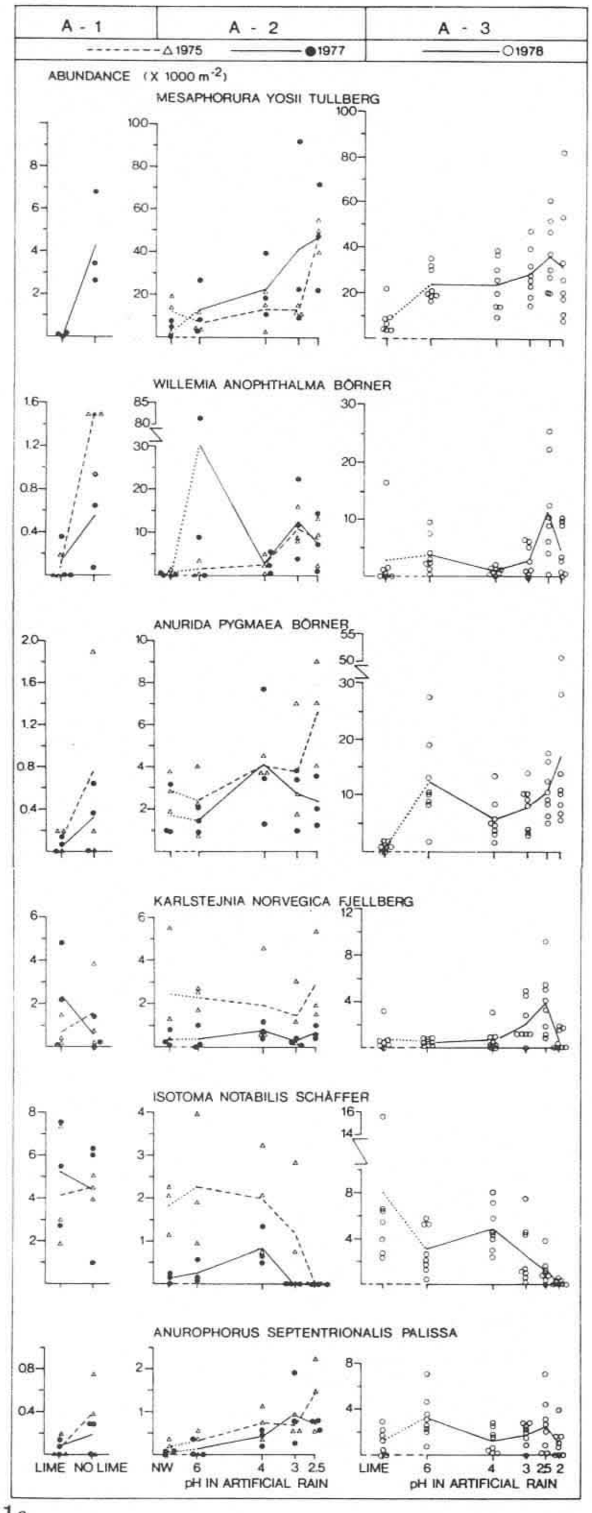
HÅGVAR & AMUNDSEN (1981), for example, found that the population densities of several mite species were affected by changes in soil *p*H. The present paper deals with Collembola and Protura from the same series of samples. Preliminary reports on the effects of acidification and liming on these two groups were published by HÅGVAR & ABRAHAMSEN 1977a, b) and HÅGVAR (1978).

2. Materials and methods

Habitats, experimental design and sampling have been described by HÅGVAR & AMUNDSEN (1981). Detailed data on plot size, soil characteristics, ground water chemistry, vegetation and experimental design have been published by ABRAHAMSEN *et al.* (1976) and STUANES & SVEISTRUP (1979). Only the main points are reviewed here.

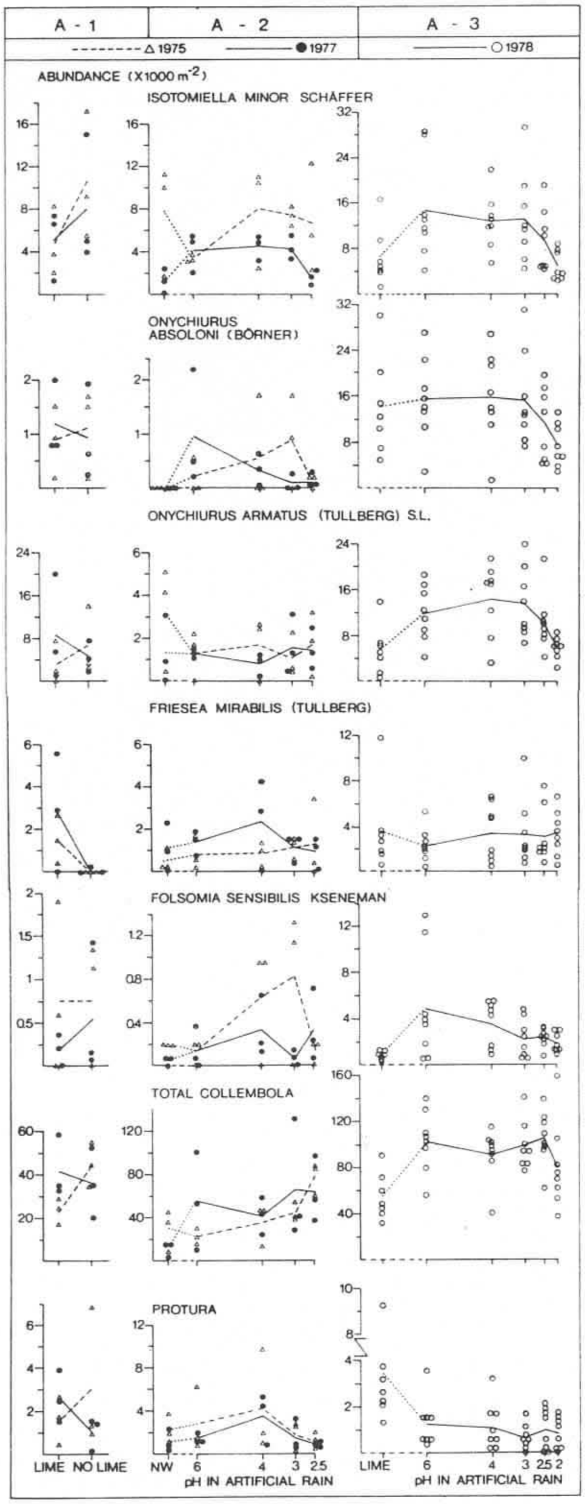
The experimental site, situated on a flat plain of glacifluvial sandy deposits about 40 km N of Oslo, had an Eu-Piceetum Myrtilletosum vegetation type and podzol/semipodzol soils (Typic Udipsamment, USDA classification).

Samples were taken from three different coniferous forest habitats in which the soil *p*H had been changed by liming (crushed limestone, $CaCO_3$), or by artificial acid rain (ground water with added sulphuric acid). The *p*H of the artificial rain was 6 (pure ground water), 4, 3, 2.5 and 2. Because natural precipitation came in addition, the weighted annual mean *p*H of the treatments were 4.5, 4.2, 3.5, 3.0 and 2.5, respectively (STUANES 1980). The plots had been treated for 2—5 years before sampling.



1a

Fig. 1. Effect of acidification and liming on the most abundant Collembola species, total Collembola and total Protura to a depth of 6 cm. The treatments are indicated at the bottom of the figure. NW = not watered. The points represent plot means, and lines connect treatment means. In each plot, 10—14 samples of 5.3 or 10 cm^2 were taken. Information about the habitats (A-1, A-2, A-3), as well as treaments and soil acidity, are given in the text.


A - 1
A - 2
A - 3
1975
1977
1978
ABUNDANCE (X1000 m⁻²)
ISOTOMIELLA MINOR SCHÄFFER
ONYCHIURUS ABSOLONI (BÖRNER)
ONYCHIURUS ARMATUS (TULLBERG) S.L.
FRIESEA MIRABILIS (TULLBERG)
FOLSOMIA SENSIBILIS KSENEMAN
TOTAL COLLEMBOLA
PROTURA
LIME NO LIME
NW 6 4 3 2.5
pH IN ARTIFICIAL RAIN
LIME 6 4 3 2.5 2
pH IN ARTIFICIAL RAIN

1b

Experiment A-1: *Pinus contorta* DOUGL. (appr. 4 m high at sampling). Unlimed and limed plots (3,000 kg CaO ha^{-1}). Three replications. Sampling in October 1975 (10 samples per plot, each 5.3 cm^2) and October 1977 (14 samples per plot, each 10 cm^2).

Experiment A-2: *Picea abies* (L.) KARST. (appr. 5 m high at sampling). Unwatered plots and plots treated with artificial rain of *p*H 6 (control), 4, 3, and 2.5. Three replications. Sampling in October 1975 (10 samples per plot, each 5.3 cm^2) and September 1977 (14 samples per plot, each 10 cm^2).

Experiment A-3: *Picea abies* and *Pinus silvestris* L. (appr. 0.5 m high at sampling). Unlimed and limed plots (4,500 kg CaO ha^{-1}). Artificial rain of *p*H 6 (control), 4, 3, 2.5 and 2. Eight replications (four *Picea abies* and four *Pinus silvestris* plots) were pooled, as the microarthropod fauna was quite similar in spruce and pine plots. Sampling in October 1978 (10 samples per plot, each 5.3 cm^2).

Samples were taken to 6 cm depth, in 2 or 3 cm thick sections. The 0 layer was approximately 3 cm thick, and the underlying eluvial layer (E) had a similar thickness. The animals were extracted according to MACFADYEN (1961).

All statistical treatments, both regarding abundance and dominance, were based on the mean values of the replications (each calculated from the 10—14 soil cores). In most cases, the analysis of variance was used, with estimation of "least significant difference". Student's t-test was applied when only two categories were compared (for instance limed versus control plots).

3. Results

3.1. Soil chemistry and vegetation

The soil *p*H and base saturation of untreated, limed and acidified plots at the sampling times were as reported by HÅGVAR & AMUNDSEN (1981). In general, liming considerably increased the *p*H value of the raw humus, from original values between 3.9 and 4.8 to values between 6.2 and 6.9. Artificial "rain" of *p*H 3 or lower reduced soil *p*H. In experiment A-2, application of *p*H 2.5-rain reduced the *p*H of the raw humus from about 4.1 (control plots) to about 3.8. In experiment A-3, *p*H 2-rain reduced the raw humus *p*H from about 3.9 to 3.4.

The moss vegetation was markedly reduced on plots given *p*H 3-rain, and after stronger treatments, mosses were virtually absent.

3.2. Abundance of Collembola and Protura

Fig. 1 illustrates the reactions to different treatments of the most abundant Collembola species, total Collembola and total Protura.

The reactions form a rather complex picture. In Table 1, all significant effects on abundance have been listed. Some species have reacted to both liming and acidification, some only to one of these treatments, and some species did not show significant reactions to any treatment. In several cases, the reaction patterns were supported by non-significant trends.

The most consistent reactions were found in *Mesaphorura yosii* which is the dominant species in the area. Liming clearly reduced its abundance (data from A-1 1975 are, however, missing), while strong acidification gave a significant increase in A-2 (1975) and a corresponding trend in the two other acidification curves. *Willemia anophthalma* was significantly reduced in one liming experiment (A-1, 1975) and showed increased abundance in two acidification experiments A-2, 1975 and A-3). The increase was found in the second strongest treatment (Table 1), indicating that very strong acidification may again reduce the abundance. A similar picture was obtained for *Karlstejnia norvegica* in the acidification experiment A-3.

The abundance of *Anurida pygmaea* was significantly reduced in one liming experiment (A-3), and the same trend appeared in the two other liming experiments (Fig. 1).

Three species did not react significantly to liming, but were reduced in abundance in certain acidification experiments: *Isotoma notabilis*, *Lepidocyrtus cyaneus* Tullberg (low abundance and not drawn in Fig. 1), and *Isotomiella minor* (*cf.* Table 1). A statistically significant increase in abundance at the *p*H 4-treatment in *Isotoma notabilis* is difficult to understand, as the soil chemistry was practically unchanged by this treatment.

One species, *Onychiurus armatus s. l.*, was reduced in abundance both by liming and acidification (experiment A-3). Reduced abundance on limed plots in this experiment was observed also in *Folsomia sensibilis* and *Anurophorus septentrionalis*.

Table 1. Significant effects of liming or acidification on the Collembola fauna in various field experiments in coniferous forest (0—6 cm depth)

	Effect of liming[1]			Effect of acidification[2]			
Experiment	A-1	A-1	A-3	A-2	A-2	A-3	
Sampling year	1975	1977	1978	1975	1977	1978	
Mesaphorura yosii	No data	—*[3,4]	—***	+ 2.5—6*** 2.5—5*** 2.5—4***			
Karlstejnia norvegica						+ 2.5—6*** 2.5—4*** 2.5—3* — 2.5—2***	
Willemia anophthalma	—***			+ 3—6* 3—4*		+ 2.5—6** 2.5—4*** 2.5—3*** — 2.5—2*	
Isotoma notabilis					— 2.5—4** 3—4**	— 2—6** 2—4*** 2—3* + 4—6*	2.5—6* 2.5—4*** 3—4*
Lepidocyrtus cyaneus					— 2.5—6** 2.5—4** 3—6** 3—4**		
Isotomiella minor						— 2—6** 2—4* 2—3*	
Onychiurus armatus s. l.			—*			— 2—6* 2—4** 2—3**	
Anurida pygmaea			—**				
Folsomia sensibilis			—*				
Anurophorus septentrionalis			—*				
Collembola, **Total**	—*		—**	+ 2.5—6** 2.5—4** 2.5—3*			
Protura			+*				

[1] Liming effects were related to unlimed control plots.
[2] All effects of acidification are specified, showing between which treatments the reduction or increase was significant. The figures thus indicate pH in artificial rain.
[3] — indicates reduced abundance, and + increased abundance.
[4] Levels of significance: * = P ≦ 0.05, ** = P ≦ 0.01 and *** = P ≦ 0.001.

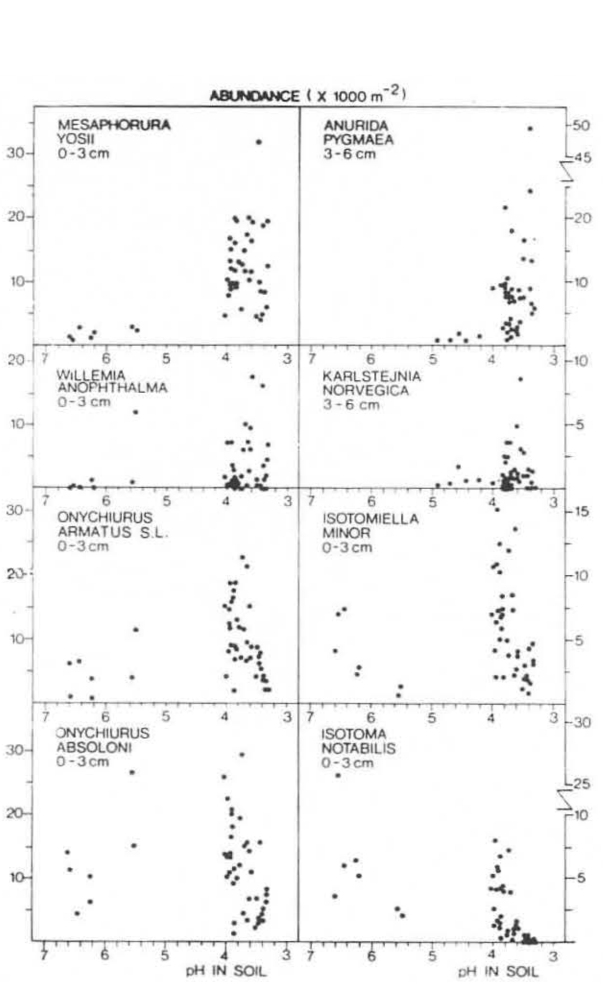


Fig. 2. Abundance of some common species related to the soil acidity (pH) of the experimental plots. Each point represents the mean of 10 samples, each 5.3 cm^2 (experiment A-3).

The total number of Collembola was significantly reduced by liming in two experiments (A-1, 1975 and A-3), and increased in one acidification experiment (A-2, 1975).

Protura numbers were unaffected in most experiments, but increased significantly following liming in A-3.

In Fig. 2, the abundance data for eight species from the A-3 sampling have been related directly to soil pH. Unfortunately the number of observations at pH values above four are relatively few, and most plots are from soils with pH values between pH 3.3 and 4.0. However, a trend for increased abundance with increased soil acidity is apparent for the four upper species. The pH range between 3.3 and 4.0 may evidently be of great importance for certain species. This is especially well documented in *Isotoma notabilis*, which is practically eliminated at pH 3.3.

In experiment A-2, abundance data were also collected from plots which were not watered (Fig. 1). No significant effects of watering alone were observed.

The number of collembolan species was not found to be influenced by liming or acidification.

3.3. Dominance

Fig. 3 shows effects on dominance in the most common species from the A-3 experiment. Changes in dominance due to liming were significant in *Mesaphorura yosii* ($P < 0.05$),

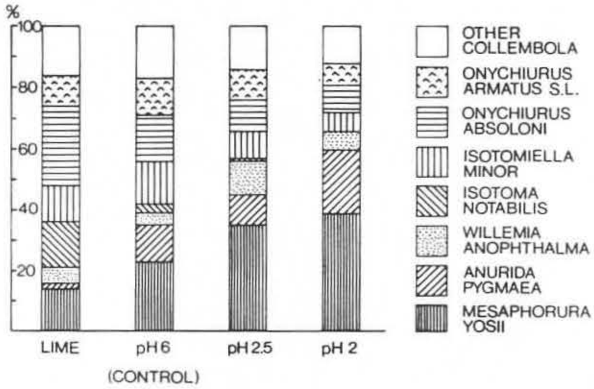


Fig. 3. Effect of acidification (the two most extreme treatments) and liming on the relative dominance of the most common Collembola species (experiment A-3). The diagram represents the mean situation at each treatment. Note that the *p*H values refer to *p*H of the artificial rain, and not to soil *p*H.

Anurida pygmaea ($P < 0.001$) and *Isotoma notabilis* ($P < 0.05$). Acidification affected the dominance in *Mesaphorura yosii* ($P < 0.05$), *Willemia anophthalma* ($P < 0.05$, *p*H 2.5), *Isotomiella minor* ($P < 0.01$) and *Isotoma notabilis* ($P < 0.01$). In *Onychiurus absoloni*, the dominance in limed and the strongest acidified plots differed ($P < 0.01$).

3.4. Vertical distribution

A complete survey of reactions to limining and acidification in each vertical layer is given in Table 2. In several cases, the reactions were restricted to one layer. Such "local" effects could be found even when the total abundance (0—6 cm) was not significantly influenced. Conversely, in *Folsomia sensibilis*, the negative effect of liming on total abundance was not significant in any of the layers.

Reactions to liming in Collembola always involved a reduction in abundance, while acidification induced increased abundance in some species and reduced abundance in others. The greatest number of reactions to liming were noted in the uppermost layer. Similarly, all negative reactions to acidification appeared in the upper 2 or 3 cm. However, increased abundance due to acidification was also often observed below 3 cm depth.

Protura numbers were unaffected in most experiments, but the observed increase in the 0—3 cm layer in one liming experiment is in contrast to all Collembola reactions.

Quantitative information on the changes in different layers after liming and acidification is presented for three species in Fig. 4. The abundance on control plots (given only ground water of *p*H 6) has been set to 100% for each vertical layer. Data from some layers have been omitted due to low numbers. All effects of acidification were related to the strongest treatment in each experiment. In all three species, several non-significant trends support the picture drawn by the significant reactions. The most remarkable response was the 16-fold increase of *Mesaphorura yosii* in the 3—6 cm layer (A-2, 1975).

In Fig. 5, significant effects of liming and acidification on the overall vertical distribution pattern are presented (Student's t-test based on the percentage values in each layer). All effects on the vertical distribution, both due to liming and acidification, imply a shift towards greater depths. This change is apparent also in species which increase in numbers on acidified plots (*cf.* Tables 1 and 2).

4. Discussion

4.1. Abundance

Present results agree well with those from comparable studies by Bååth *et al.* (1980), Hågvar & Abrahamsen (1980), Hågvar & Kjøndal (1981a), and Huhta *et al.* (1983).

Table 2. A total survey of all significant ($P \leq 0.05$) effects on abundance due to liming or acidification, when the material is analysed at each depth interval

	Effect of liming										Effect of acidification[1]									
Experiment	A-1			A-1				A-3			A-2			A-2				A-3		
Sampling year	1975			1977				1978			1975			1977				1978		
Depth (cm)	0—3	3—6	0—6	0—2	2—4	4—6	0—6	0—3	3—6	0—6	0—3	3—6	0—6	0—2	2—4	4—6	0—6	0—3	3—6	0—6
Mesaphorura yosii				—		—	—	—	—	—	+	+	+	+		+				
Karlstejnia norvegica																		+[2]	+[2]	+[2]
Willemia anophthalma	—		—								+[3]		+[3]					+[2]		+[2]
Friesea mirabilis																			+	
Isotoma notabilis																		—		—[4]
Lepidocyrtus cyaneus														—			—			
Isotomiella minor																		—		—
Onychiurus absoloni																		—		
Onychiurus armatus s. l.								—		—								—		—
Anurida pygmaea								—	—	—										
Folsomia sensibilis										—										
Anurophorus septentrionalis								—		—										
Collembola, **total**	—		—					—	—	—	+	+	+					—		
Protura								+		+										

[1] In this table, effects of acidification refer to the abundance at the most acidified plots, compared to the control. A few exceptions exist under the remarks[2] and [3].
[2] The effects refer to pH 2.5-treated plots. Abundance was significantly reduced again at the pH 2-treated plots.
[3] The effects refer to pH 3-treated plots. Mean abundance was somewhat lowered again at pH 2.5-treated plots.
[4] A significant increase at the pH 4-treatment (as indicated in Table 1) is probably an artefact.

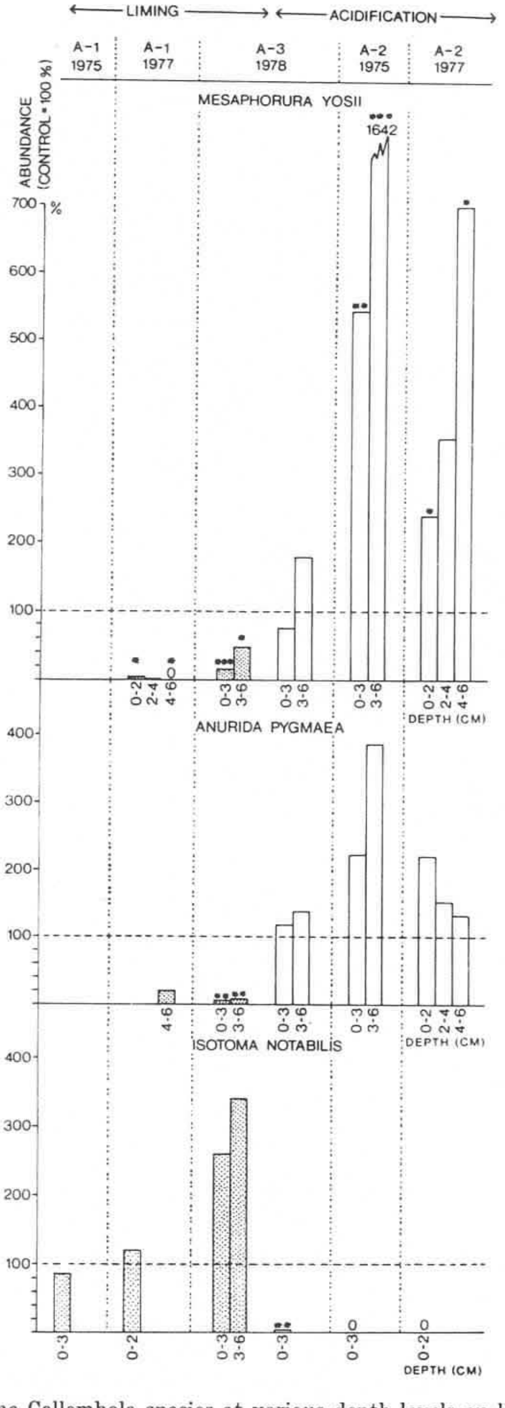


Fig. 4. Abundance of some Collembola species at various depth levels on limed and most acidified plots, given in per cent of the abundance in corresponding depth levels on control plots. Shaded columns: limed plots, open columns: acidified plots. Significant differences from control are indicated: * = $P \leq 0.05$; ** = $P \leq 0.01$, and *** = $P \leq 0.001$.

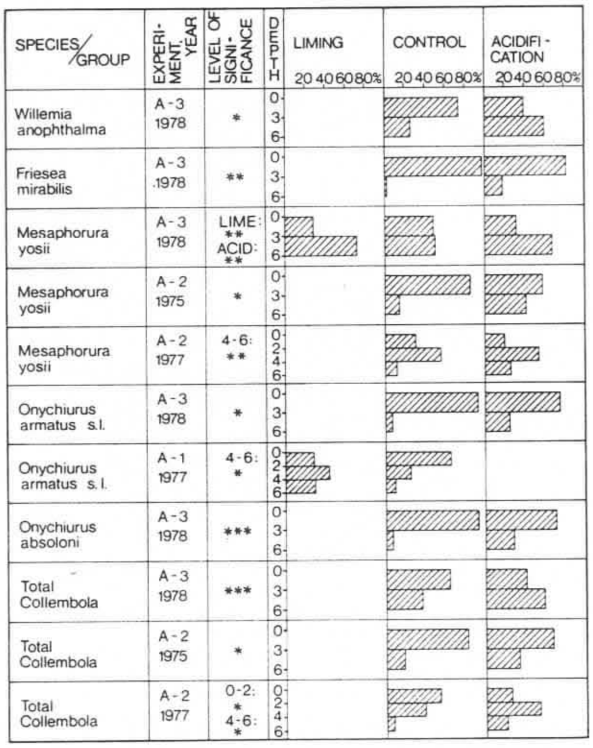


Fig. 5. Significant effects of acidification (strongest treatment) and liming on the vertical distribution pattern of various species, and of total Collembola. On each treatment, the total abundance in the 0—6 cm layer was set to 100 %. Differences from the control are given with the same symbols as in Fig. 4.

Mesaphorura yosii and *Anurida pygmaea* are "acidophilic" or acid-tolerant species which are often reduced in numbers by liming. Conversely, the abundance of *Isotoma notabilis* is generally reduced by acidification, and liming may give increased populations (*cf.* also Fig. 4). Reduced abundance of *Lepidocyrtus cyaneus* and *Isotomiella minor* in acidified soil has also been found in previous studies, as well as negative reactions in *Onychiurus armatus s. l.* to both liming and acidification. The observed increase of *Friesea mirabilis* in acidified soil in the present study (A-3, 3—6 cm) is, however, in contrast to the results of Hågvar & Abrahamsen (1980).

Huhta *et al.* (1983) also found that the total Collembola numbers were reduced by liming. Acidification to a certain extent can obviously increase the abundance of Collembola (A-2 1975, mainly due to *Mesaphorura yosii*), while stronger acidification, as in experiment A-3 or the greenhouse experiment of Hågvar & Kjøndal (1981 a), gave significant reductions in total Collembola.

The observed increase in Protura populations on limed plots in experiment A-3 is supported by a corresponding trend in a previous experiment, where limed raw humus samples were colonised to a larger extent than acidified samples (Hågvar & Abrahamsen 1980).

Theoretically, the observed reactions might be due to the chemicals applied, and not to soil pH as such. However, several of the described relationships can be found also in soils differing naturally in pH, without any influence of excess lime or sulphuric acid. For instance, *Mesaphorura yosii*, *Willemia anophthalma* and *Anurida pygmaea* are typical inhabitants of raw humus (with pH values between 3.5 and 4.0) and are rare or absent in mull soils of higher pH. *Isotoma notabilis*, however, shows the opposite distribution (Hågvar 1982).

HUHTA *et al.* (1983) showed that several published effects of fertilizers on the soil fauna (including Collembola) may be related not to the chemicals as such, but rather to the *p*H changes which they induce.

At extreme treatments, however, direct effects of the chemicals are possible. For instance, HÅGVAR & KJØNDAL (1981a) found that frequent application of diluted sulphuric acid of *p*H 2 reduced the abundance of many species of Collembola. The several negative reactions to the *p*H 2-treatment in experiment A-3 may also represent a kind of "shock-effect" (Table 2).

It is concluded that artificial changes of soil *p*H can induce large effects on the quantitative composition of the collembolan fauna. Furthermore, the abundance of certain species seems to be generally related to soil acidity.

4.2. Vertical distribution

In many species and groups of Acari also, the treatments profoundly affected the vertical distribution (HÅGVAR & AMUNDSEN 1981). Just as for Collembola, the mean depth of Acari populations was increased in limed and acidified soils. The only exception was Prostigmata in which the relative proportion increased in the upper few centimetres of limed plots.

Since the soil chemical changes on limed and acidified plots were most pronounced in the upper 2—3 cm (HÅGVAR & AMUNDSEN 1981), it is reasonable that species which were reduced in abundance achieved a deeper distribution. However, species which achieved increased abundance in acidified soil also shifted their mean vertical position to greater depths by increasing their numbers mainly below 2 or 3 cm depth. Even these "acidophilic" species seem to avoid direct contact with the strongest concentrations of sulphuric acid (*p*H 2.5 and 2). In all the three acidification experiments, therefore, the combined effect of different reactions induced a deeper distribution of total Collembola numbers (Fig. 5).

4.3. Population regulating mechanisms

The simplest way to explain relationships between population size and soil acidity would be to postulate a direct influence of the substrate's *p*H on reproduction and longevity. Certain previous studies indicate that such relationships may exist (MACLAGAN 1932, ASHRAF 1969, HUTSON 1978). However, preliminary experiments with cultures of *Mesaphorura yosii* in raw humus samples adjusted to different *p*H levels did not reveal a more rapid population growth at the lowest *p*H levels (HÅGVAR, unpublished). The relationships observed under field conditions are probably indirect, as soil acidity may influence important factors such as competition, predators/parasites, food conditions and others.

As most of the species in Table 2 ingest fungal hyphae as part of their diet (POOLE 1959, BÖDVARSSON 1970 and 1973, HÅGVAR & KJØNDAL 1981b, HÅGVAR unpubl.), changes in fungal composition, biomass or productivity might theoretically affect collembolan populations. Species composition and productivity of soil fungi have not been studied on the experimental plots, but an analysis contemporary with the microarthropod sampling in area A-3 failed to show any significant effect of *p*H 3- and *p*H 2-treatments on the amount of total and FDA-active hyphae (BÅÅTH *et al.* 1979).

Neither in the present experiment nor in the studies by BÅÅTH *et al.* (1980) or HÅGVAR & ABRAHAMSEN (1980) were the populations of the larger, predatory Gamasina drastically affected by the artificial changes in soil *p*H. If any of the observed effects on Collembola are caused by changes in predation pressure, other groups, for instance certain Prostigmata, must be responsible. Predation by macrofauna is unlikely to be important, since most of the relevant Collembola species are not surface active.

HÅGVAR & ABRAHAMSEN (1980) and HÅGVAR & AMUNDSEN (1981) found that in several species of Collembola and Acari, the proportion of juveniles was highest at those *p*H levels where the total population of each species was greatest. This indicated a relation between reproductive success and soil *p*H, but it might also be explained by variations in the mortality rates of juveniles.

The "abnormal" response of *Mesaphorura yosii* to soil *p*H in pure culture (referred to above) indicates that the field response to soil *p*H changes is dependent on the presence of

other components of the soil fauna. This points to competition as a major regulating factor. Regarding the microarthropod fauna as a whole (*cf.* HÅGVAR & AMUNDSEN 1981), it is striking that the species which have increased their populations in acidified soil are typical inhabitants of naturally acid soils and were already among the dominant species before the treatments started. In short, acidification of raw humus allows the dominant microarthropods to become even more abundant. It may well be that the factors initiating their increase in the acidification experiments are the same factors which induce their high dominance in naturally acid soils. Basic ecological studies of these species in raw humus, including their relations to other soil animals, may therefore help to explain the phenomena observed in the present study.

5. Acknowledgements

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6. Résumé

(Effets du chaulage et de l'arrosage artificiellement acide sur les Collemboles et les Protoures dans les forêts de conifères)

On a procédé à des expériences de chaulage ($CaCO_3$) et d'arrosage artificiellement acide (acide sulfurique dilué, traitement maximum *p*H 2) dans des podzols de forêts de conifères.

L'élévation du *p*H du sol après chaulage réduit la densité de plusieurs espèces de Collemboles. La densité globale des Collemboles a été réduite de façon significative dans deux des trois expériences réalisées. L'augmentation de la densité des Protoures fut accrue dans une des expériences.

L'abaissement du *p*H dans le sol (principalement après adjonction d'eau de *p*H 2—2,5) a engendré un modèle de réaction complexe. On a constaté une augmentation des densités de *Mesaphorura yosii*, de *Karlstejnia norvegica* et de *Willemia anophthalma*.

Le nombre total de Collemboles a augmenté en un endroit. La réduction la plus accusée a été celle des *Isotoma notabilis* parmi les espèces qui ont décliné au cours de l'acidification.

La distribution verticale des Collemboles a été affectée et par le chaulage (deux espèces) et par l'acidification (cinq espèces et les Collemboles en général). Tout changement a impliqué une élévation du pourcentage dans la couche de 3—6 cm (E, couche éluvionnaire) par comparaison avec la couche de 0—3 cm (O, humus brut).

Ni les quantités d'hyphes de champignons, ni la pression prédatrice des Gamasina de grande taille ne pourraient expliquer ces résultats. Nous émettons l'hypothèse que la compétition est un important facteur de la régulation des populations.

Mots clef: Collembola, Protura, forêt de conifères, chaulage, arrosage acide, Norvège.

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Synopsis: *Original scientific paper*

Hågvar, S., 1984. Effects of liming and artificial acid rain on Collembola and Protura in coniferous forest. Pedobiologia **27**, 341—354.

In coniferous forest with podzol soil, field experiments were performed with liming ($CaCO_3$) and artificial acid rain (diluted sulphuric acid, strongest treatment *p*H 2).

Increased soil *p*H after liming reduced the abundance of several collembolan species. In two of three experiments, the total abundance of Collembola was significantly reduced. The abundance of Protura increased in one experiment.

Reduced soil *p*H (mainly after application of water with *p*H 2—2.5) resulted in a complex reaction pattern. Increased abundance was observed in *Mesaphorura yosii*, *Karlstejnia norvegica* and *Willemia anophthalma*. Total Collembola numbers increased in one site. Among the species which declined under acidification, the most marked reduction was in *Isotoma notabilis*.

The vertical distribution of Collembola was affected both by liming (two species) and acidification (five species and total Collembola). All changes involved an increased percentage in the 3—6 cm layer (E, eluvial layer) compared to the 0—3 cm layer (0, raw humus).

Neither the amounts of fungal hyphae nor predation pressure by the larger Gamasina mites can explain the results. Competition is suggested as an important population regulating factor.

Key words: Collembola, Protura, coniferous forest, liming, acid rain, Norway.